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(54) **LIGHT-EMITTING DIODE ON A CONDUCTIVE SUBSTRATE**

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H01L 33/00 (2010.01)
H01L 21/78 (2006.01)

(52) **U.S. Cl.**

CPC ***H01L 33/0079*** (2013.01); ***H01L 21/78*** (2013.01); *H01L 2924/01078* (2013.01)

USPC **438/33**; 438/22; 438/462; 257/96; 257/100

(58) **Field of Classification Search**

CPC B82Y 20/00; H01L 33/32; H01L 21/78; H01L 23/544; H01L 2924/14; H01L 2223/55453; H01S 5/1231; H01S 5/2275

USPC 438/33, 22, 462; 257/98, 100, E33.005, 257/E33.055

See application file for complete search history.

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(57) **ABSTRACT**

A light-emitting diode (LED) device is provided. The LED device is formed by forming an LED structure on a first substrate. A portion of the first substrate is converted to a porous layer, and a conductive substrate is formed over the LED structure on an opposing surface from the first substrate. The first substrate is detached from the LED structure along the porous layer and any remaining materials are removed from the LED structure.

21 Claims, 6 Drawing Sheets

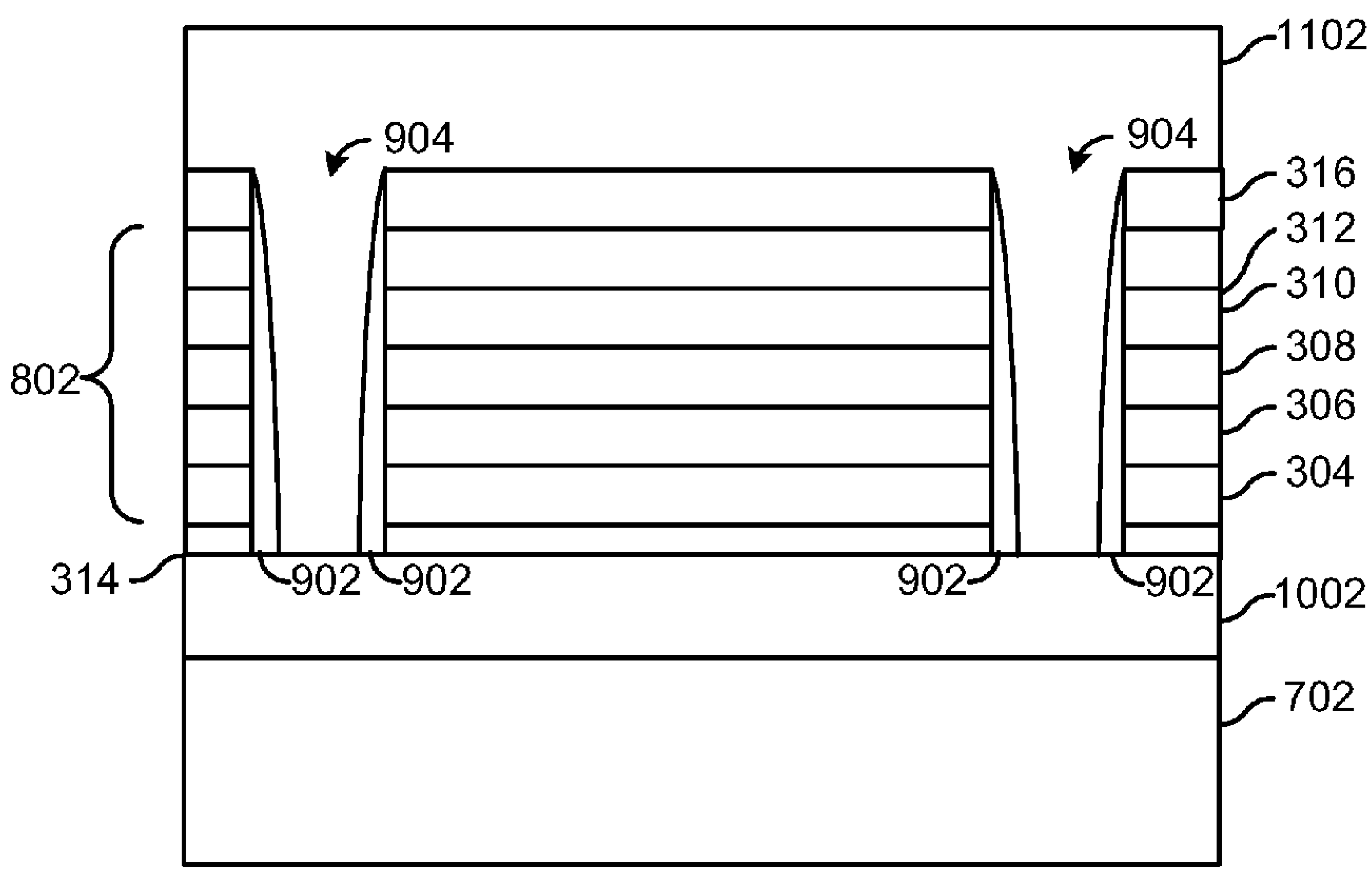

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Fig. 1

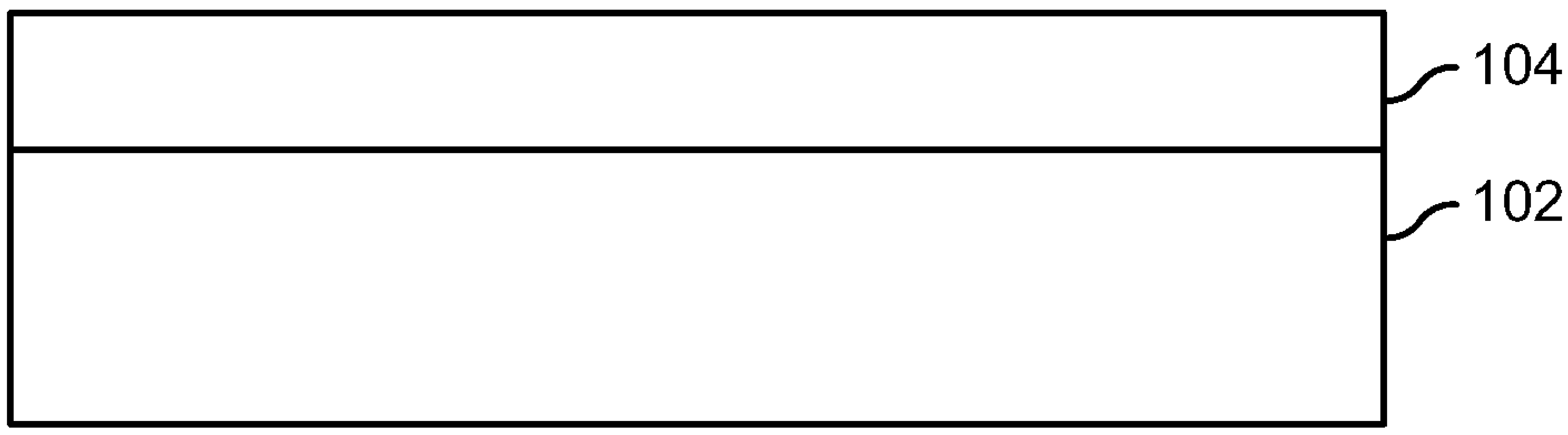


Fig. 2

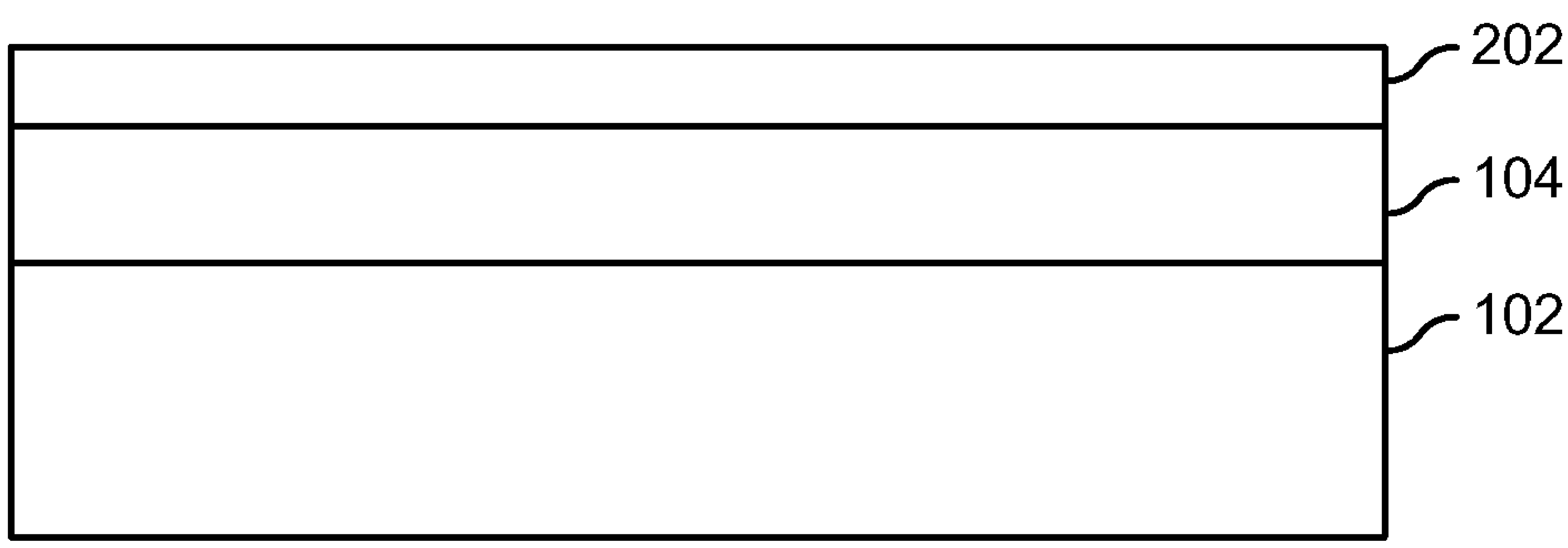
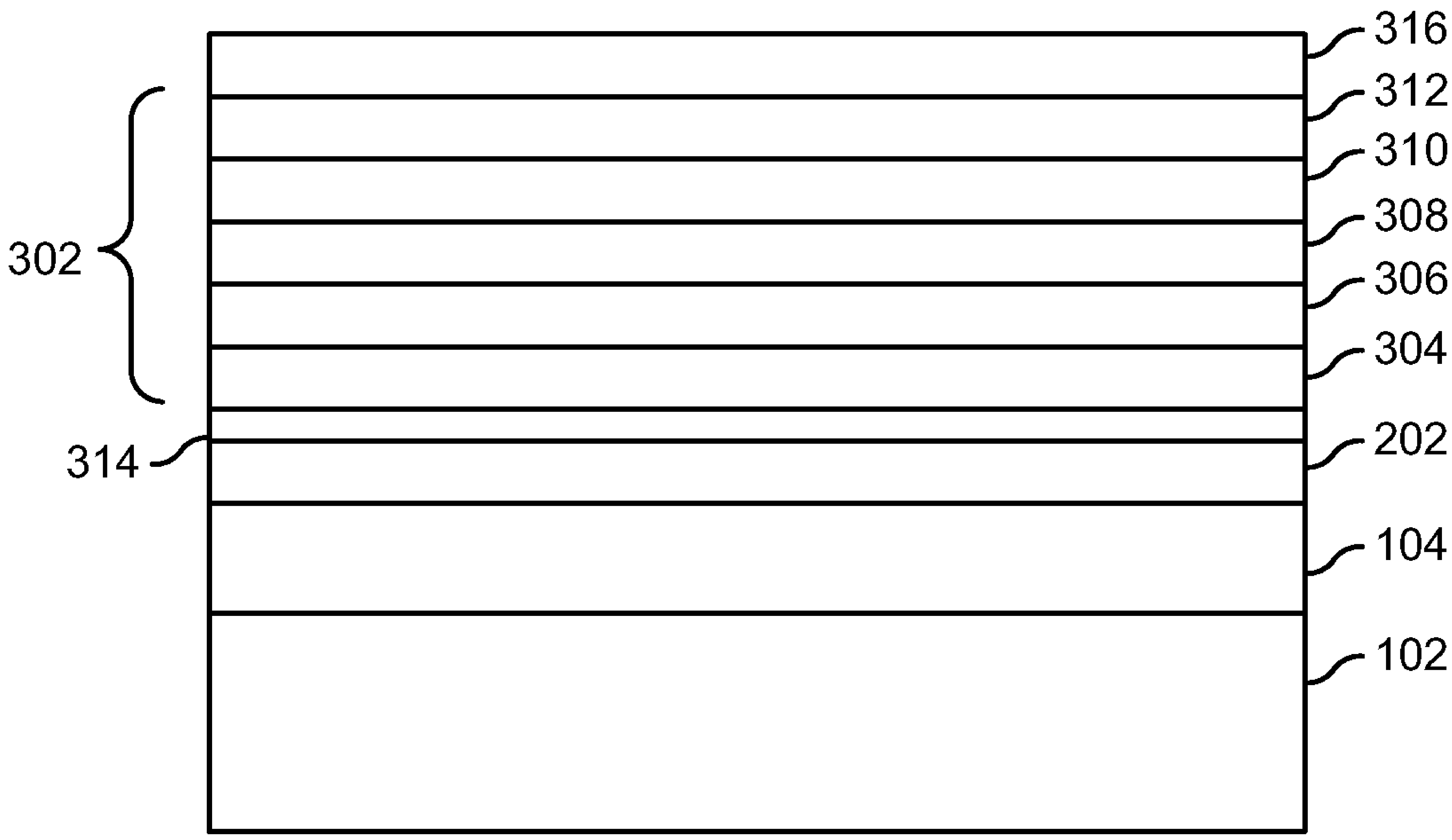


Fig. 3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312
310
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306
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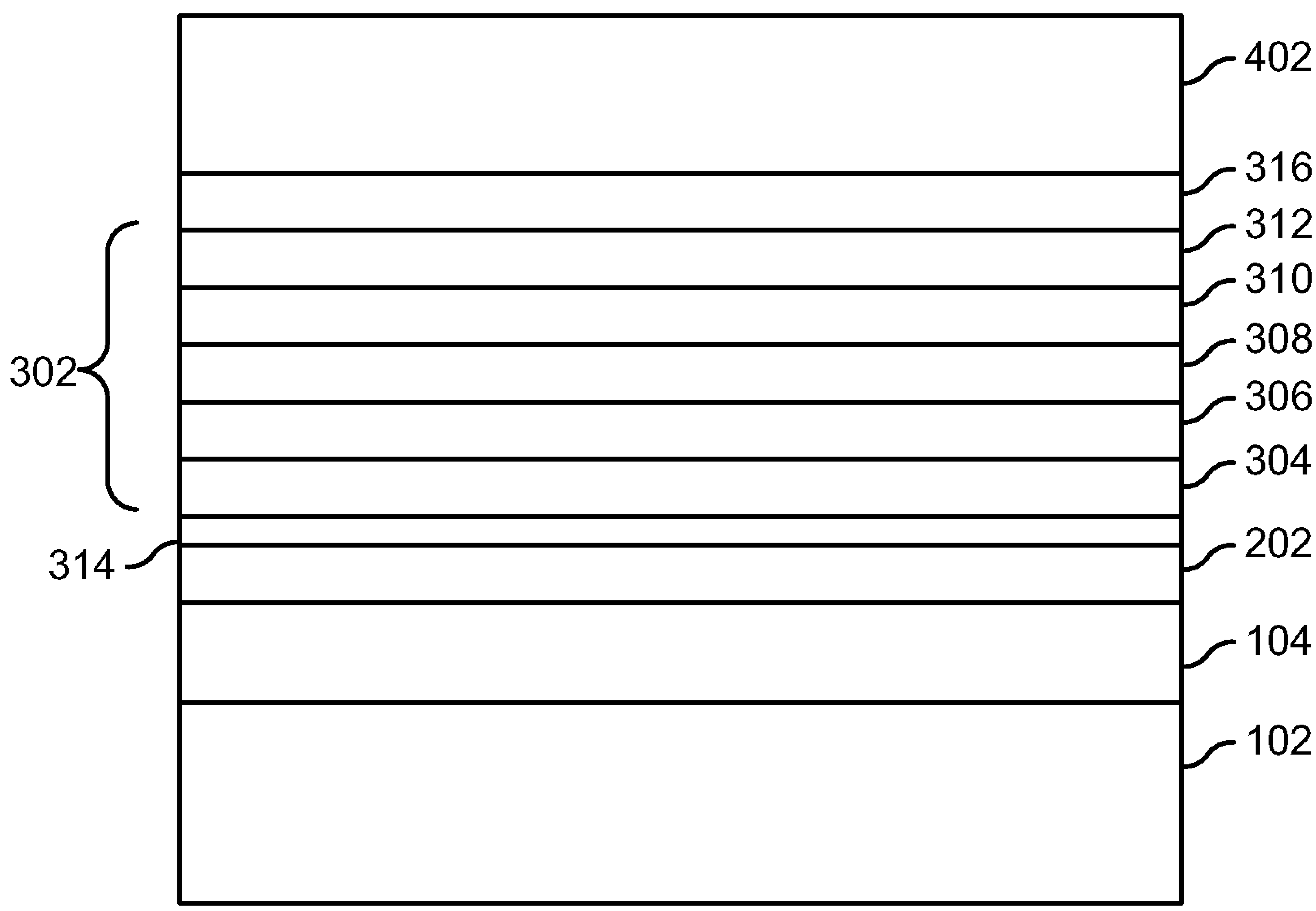
302
314
202
104
102

Fig. 4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104
102

Fig. 5

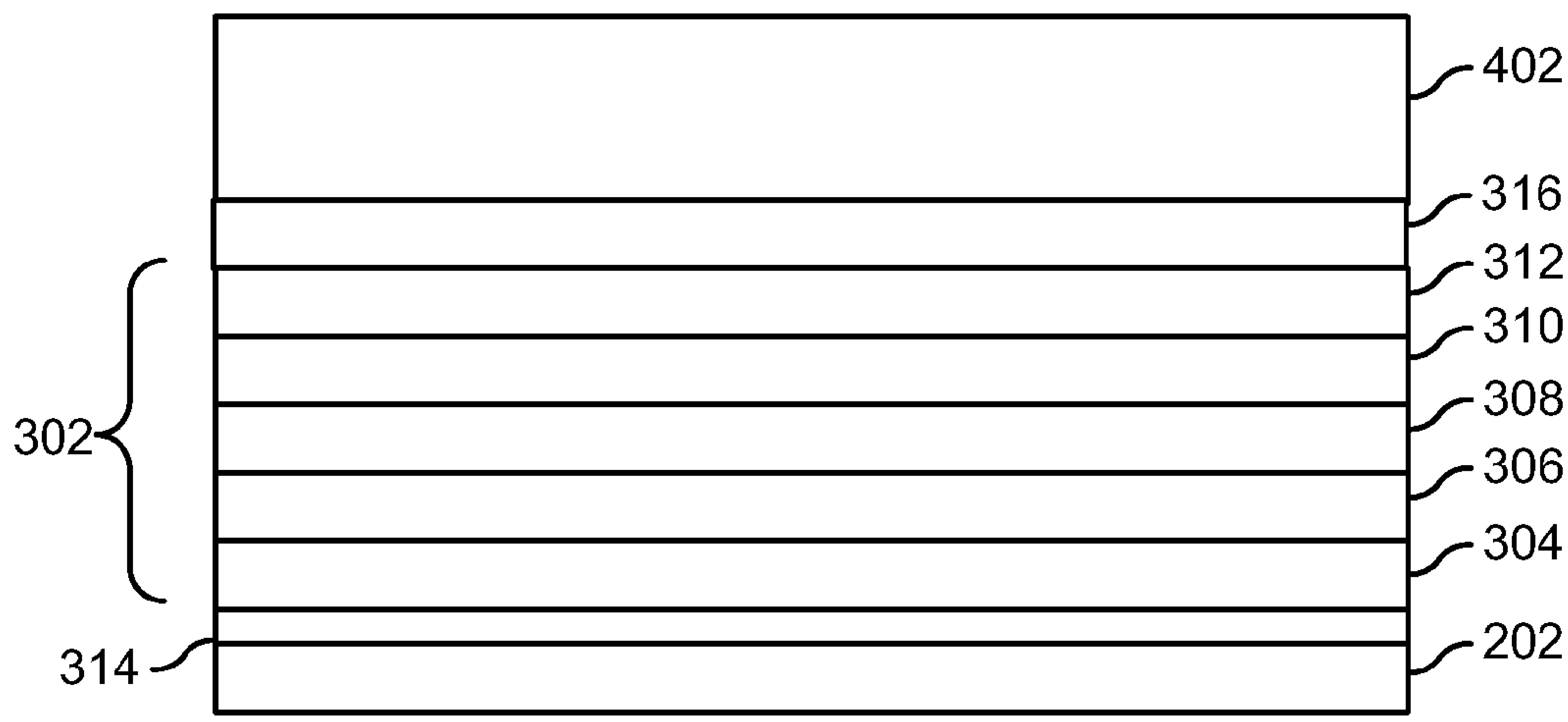
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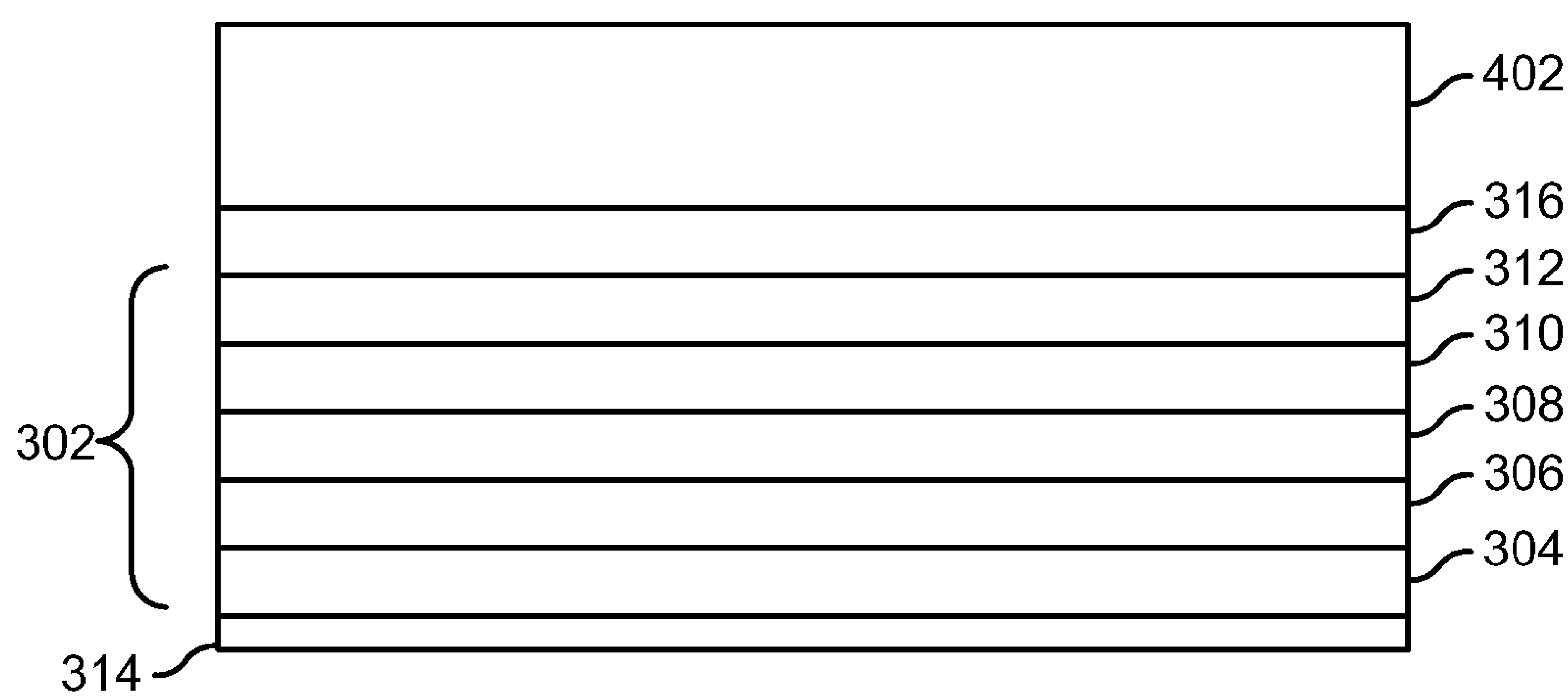
Fig. 6


402
316
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304
302
314

Fig. 7

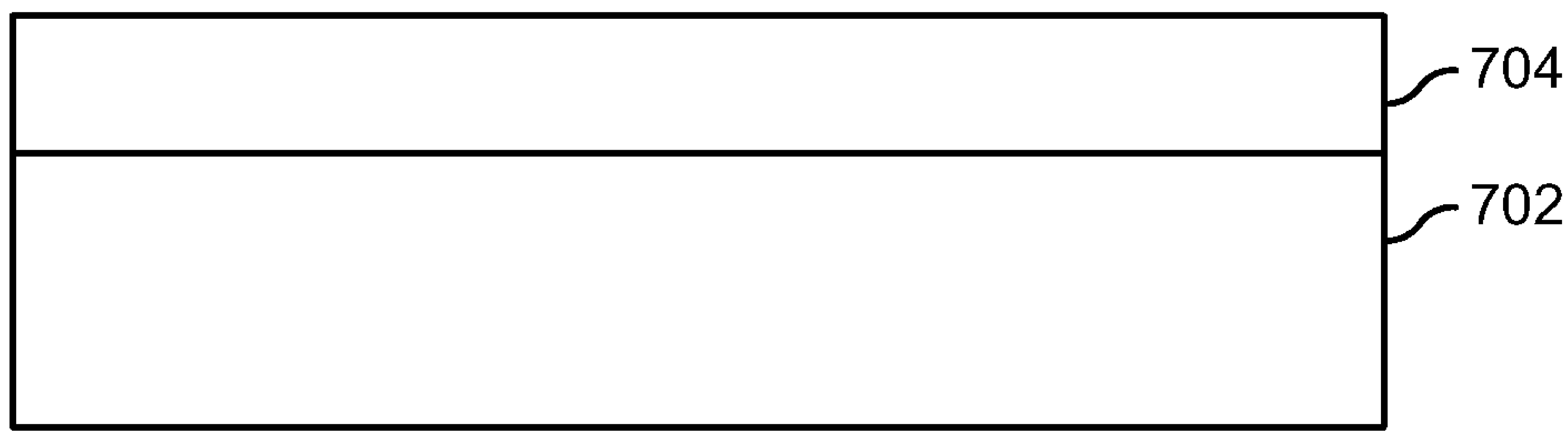


Fig. 8

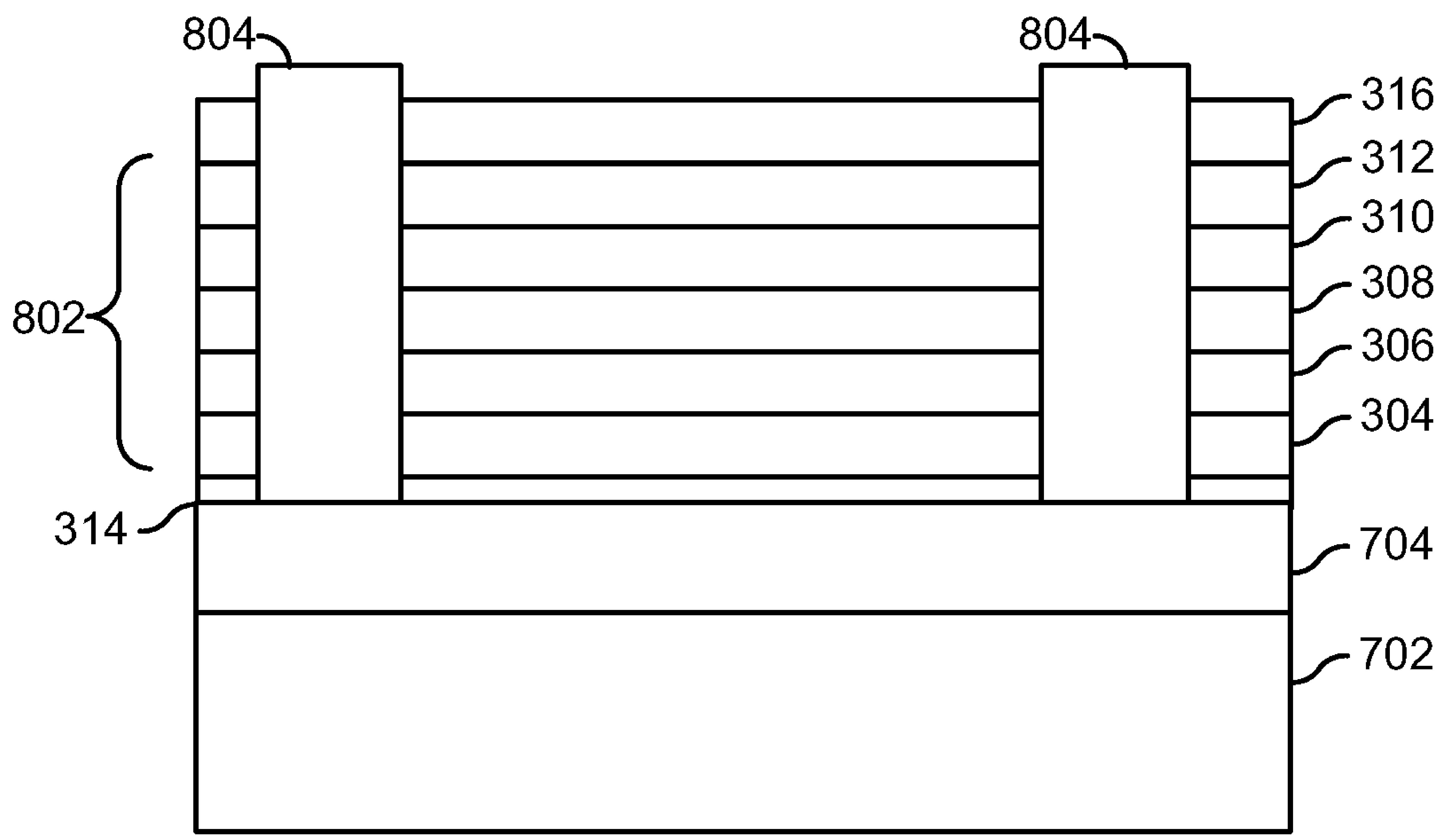
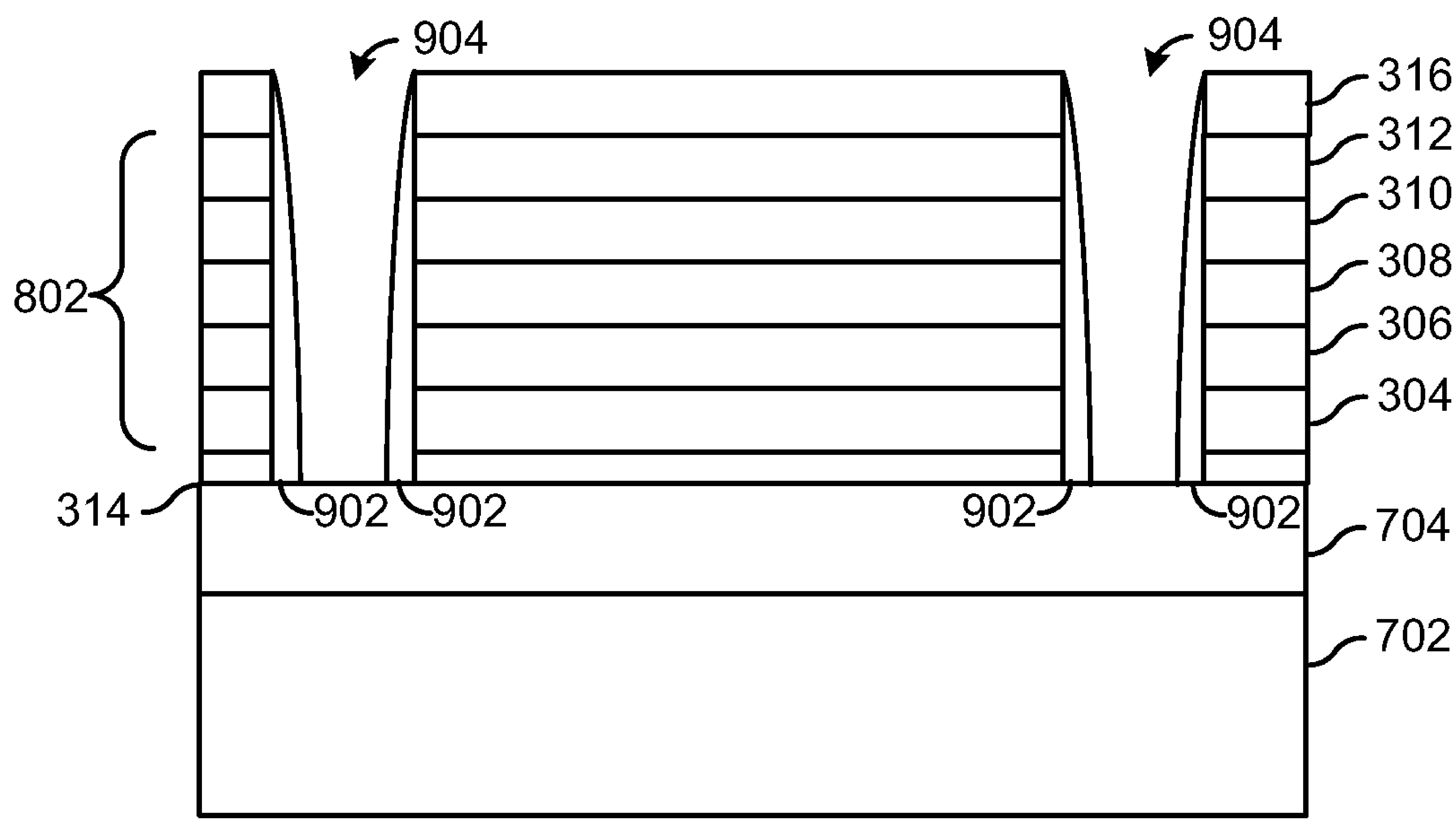


Fig. 9


904
904
316
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310
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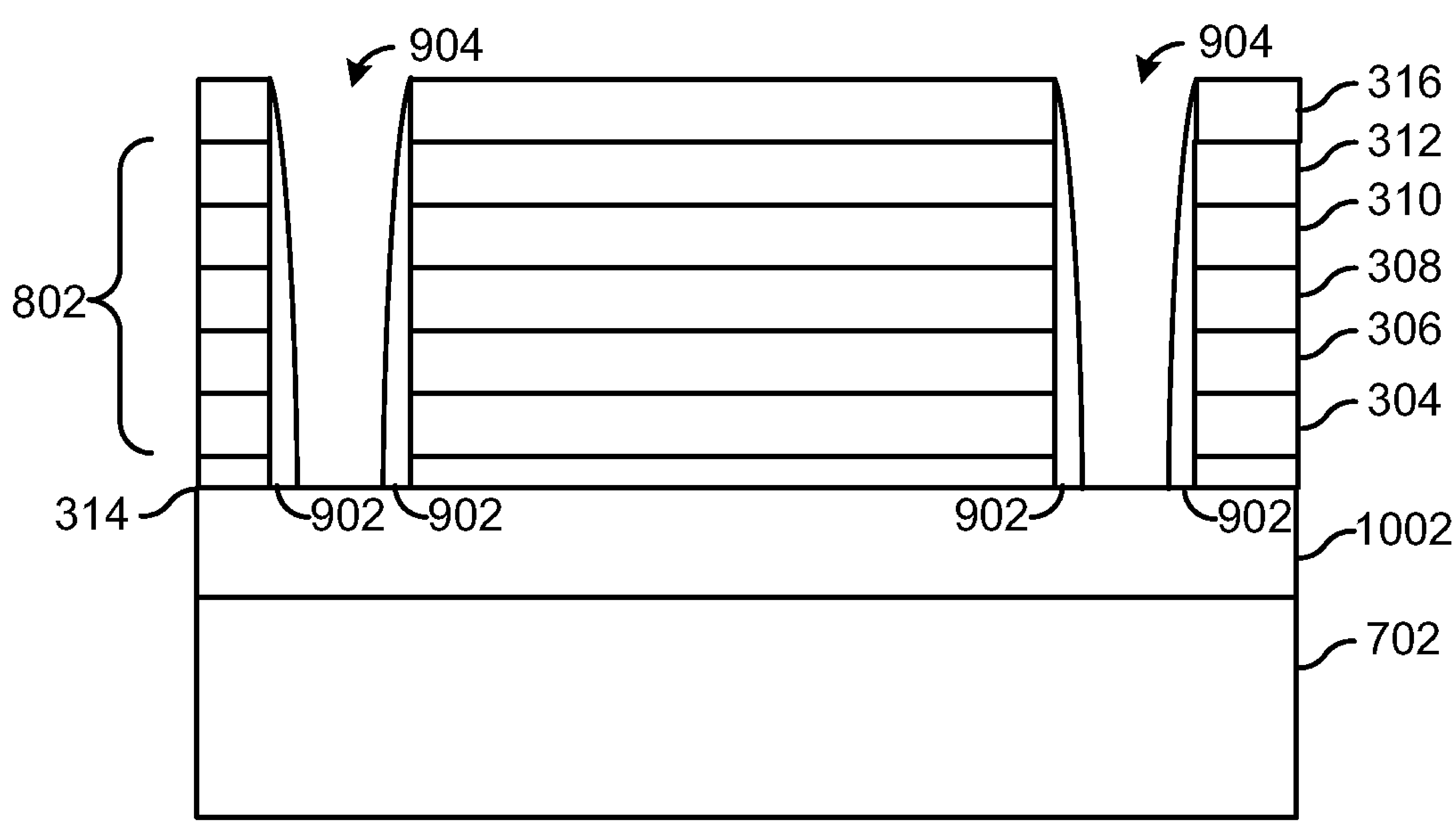
306
304
802
314
902
902
902
902
704
702

Fig. 10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902
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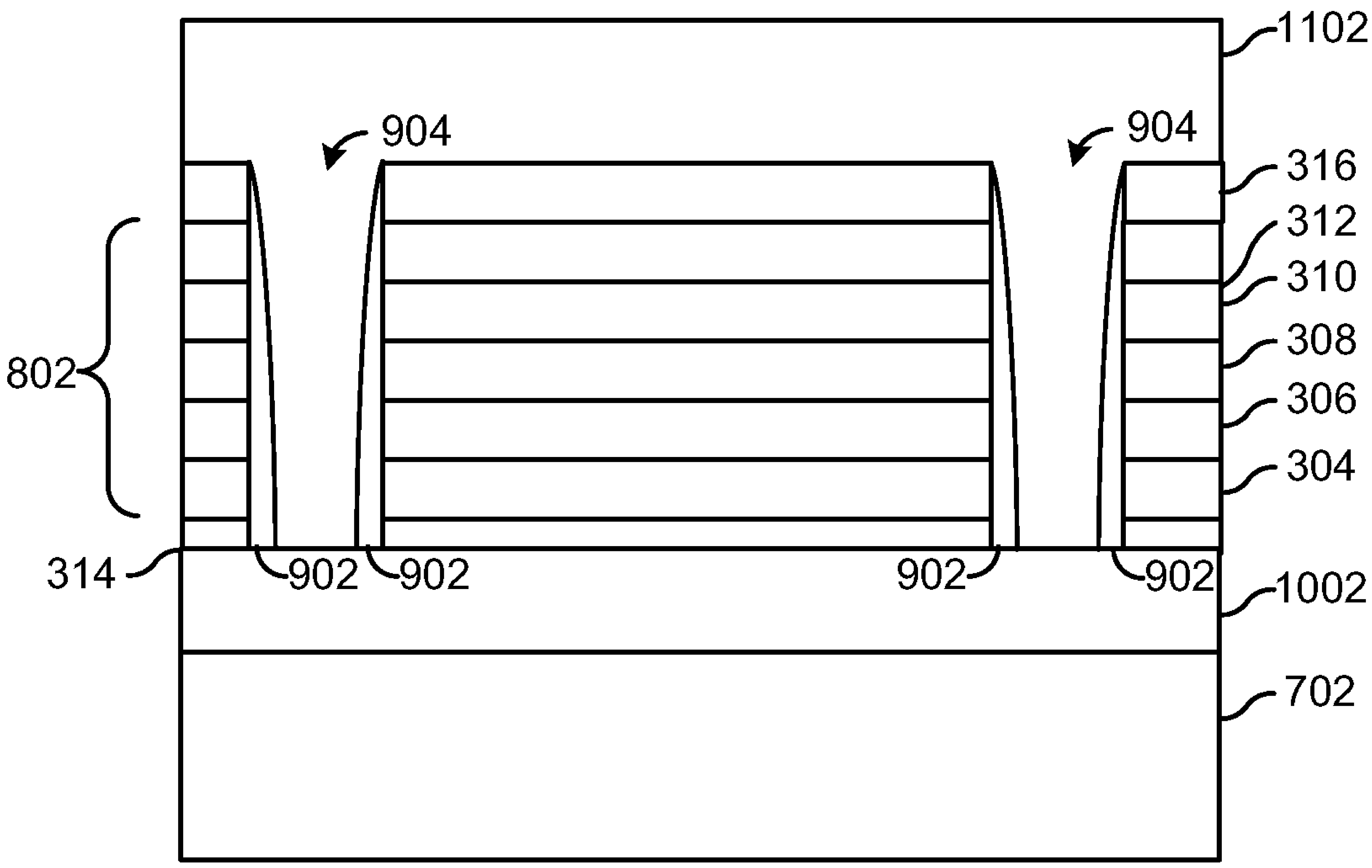
902
1002
702

Fig. 11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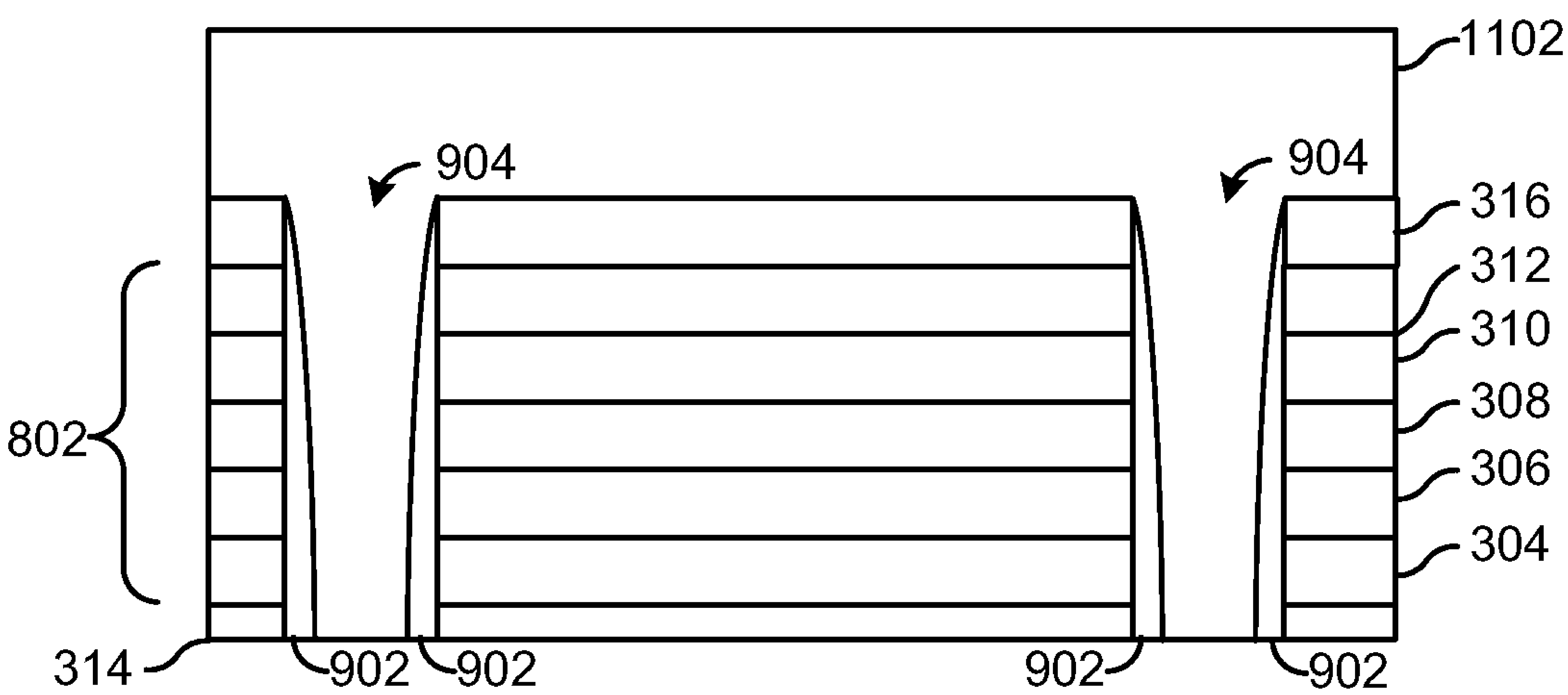
1002
702

Fig. 12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LIGHT-EMITTING DIODE ON A CONDUCTIVE SUBSTRATE

This application claims the benefit of U.S. Provisional Application Ser. No. 61/093,133, filed on Aug. 29, 2008, entitled “Light-Emitting Diode on a Conductive Substrate,” which application is hereby incorporated herein by reference.

TECHNICAL FIELD

This invention relates generally to semiconductor device manufacturing processes, and more particularly to forming crystalline group-III/V films on conductive substrates.

BACKGROUND

Light-emitting diodes (LEDs) are manufactured by forming active regions on a substrate and by depositing various conductive and semiconductive layers on the substrate. The radiative recombination of electron-hole pairs can be used for the generation of electromagnetic radiation (e.g., light) by the electric current in a p-n junction. In a forward-biased p-n junction fabricated from a direct band gap material, such as GaAs or GaN, the recombination of the electron-hole pairs injected into the depletion region causes the emission of electromagnetic radiation. By using materials with different band gaps, which emit electromagnetic radiation of different wavelengths, it is possible to create different color LEDs. The electromagnetic radiation may be in the visible range or may be in a non-visible range. Further, an LED with electromagnetic radiation emitting in a non-visible range may direct the non-visible light towards a phosphor lens or a like material type. When the non-visible light is absorbed by the phosphor, the phosphor emits a visible light.

It is desirable to use silicon substrates to form LED devices due in part to the low cost of the silicon substrates and the abundance of well-known processing techniques available for processing the silicon substrates. For vertical LED devices, the silicon substrates are used as a conductive interface to provide an electrical connection to the bottom contact layer of the LED structure. The silicon substrates, however, typically exhibit a relatively high light absorption rate, thereby negatively impacting the light efficiency of the LED device.

One method of addressing the problem of silicon substrate absorption is to use a reflective layer, such as a distributed Bragg reflector or a reflective buffer layer, to reflect some of the light away from the substrate to a light-emitting face. The reflective layer, however, may result in a poor crystal quality of the epitaxially grown group III-V layers.

Another method of addressing the problem is to remove the silicon substrate on which the III-V films forming the LED were grown, and then add a new conductive substrate. Problems associated with this method include the sacrifice of the entire silicon substrate, and the time and expense required to remove the silicon substrate.

Accordingly, there is a need for improved methods of fabricating LED devices with increased light efficiency.

SUMMARY OF THE INVENTION

These and other problems are generally reduced, solved or circumvented, and technical advantages are generally achieved, by embodiments of the present invention, which provides light-emitting diodes (LEDs).

In accordance with one aspect of the present invention, a method of forming an LED device is provided. The method comprises forming an LED structure on a substrate. After forming the LED structure, a portion of the substrate is converted to a porous layer. A conductive substrate is then formed on the LED structure. Thereafter, the LED structure, along with the conductive substrate, is separated from the substrate by selectively etching or mechanically cleaving the porous layer.

In accordance with another aspect of the present invention, a method of forming an LED device on a silicon-on-insulator (SOI) substrate is provided. The SOI substrate comprises a silicon substrate, a buried oxide layer, and a topmost silicon layer. The method comprises forming an LED structure on the topmost silicon layer of the SOI substrate. A conductive substrate is then formed on the LED structure. The buried oxide layer is then selectively etched so that the silicon substrate is separated from the topmost silicon layer and the LED structure.

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the present invention, and the advantages thereof, reference is now made to the following descriptions taken in conjunction with the accompanying drawings, in which:

FIGS. **1-6** illustrate various intermediate process steps of manufacturing a light-emitting diode device in accordance with an embodiment of the present invention; and

FIGS. **7-12** illustrate various intermediate process steps of manufacturing a light-emitting diode device in accordance with another embodiment of the present invention.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

The making and using of the presently preferred embodiments are discussed in detail below. It should be appreciated, however, that the present invention provides many applicable inventive concepts that can be embodied in a wide variety of specific contexts. The specific embodiments discussed are merely illustrative of specific ways to make and use the invention, and do not limit the scope of the invention.

Methods for forming light-emitting diodes (LEDs) and the resulting structures are provided. It should be understood that steps necessary to illustrate the inventive aspects of the invention are shown, but other processes may be performed before or after the described steps. Throughout the various views and illustrative embodiments of the present invention, like reference numbers are used to designate like elements.

FIGS. **1-6** illustrate various process steps of forming an LED on a conductive substrate in accordance with an embodiment of the present invention. Referring first to FIG. **1**, a substrate **102** is shown with a porous layer **104** formed therein. The substrate **102** is preferably a bulk semiconductor substrate, doped or undoped, preferably having a (100) surface orientation. It should be noted that while embodiments of the present invention are described in the context of using a bulk silicon substrate, other substrates may be used. For example, silicon-on-insulator (SOI) substrates, sapphire substrates, SiC substrates, and the like, may also be used. Embodiments of the present invention, however, may be particularly suited to silicon substrates due to the low cost. Furthermore, while a substrate having a (100) surface orientation is preferred, substrates having a different surface orientation, such as (110) or (111) surface orientations, may also be used.

The porous layer **104** is formed by converting a portion of the substrate **102** to a porous layer. In an embodiment in which the substrate **102** is a bulk silicon substrate, the porous layer **104** may be formed by, for example, an electro-chemical anodization process using an electrolyte composition of aqueous solution of hydrofluoric acid (about 20% by mass) and ethylic alcohol with an anodic current density of about 1 mA/cm^2 to about 200 mA/cm^2. Preferably, the substrate **102** has a thickness, before forming the porous layer **104**, of at least about 100 μm and the porous layer **104** has a thickness of about 10 Å to about 1 μm. As will be discussed in greater detail below, the porous layer **104** will act as a separation layer for separating the substrate **102** from an LED structure formed in subsequent processes.

FIG. **2** illustrates an optional step of forming a seed layer **202** over the porous layer **104** in accordance with an embodiment of the present invention. The seed layer **202** may provide a better surface and a seed layer upon which an LED structure may be epitaxially formed in subsequent processing steps. The seed layer **202** is preferably formed using an epitaxial growth of silicon (Si), though other compounds, such as silicon germanium ($Si_xGe_{(1-x)}$), silicon carbon ($Si_xC_{(1-x)}$), or the like, may also be used.

In an embodiment, a seed layer **202** of silicon is formed using a chemical vapor deposition (CVD) process using an ambient of H_2 at a temperature of about 600° C. to about 1100° C. and a pressure of about 1 torr to about 760 torr. If used, the seed layer **202** preferably has a thickness of about 1 nm to about 1000 nm. Other processes, such as a remote plasma-enhanced chemical vapor deposition (RPCVD), molecular-beam epitaxy (MBE), metal organic vapor phase epitaxy (MOVPE), hydride vapor phase epitaxy (HVPE), liquid phase epitaxy (LPE), or the like, may also be used to deposit the seed layer.

In another embodiment, an SOI substrate is used rather than the substrate **102** with the porous layer **104** and the seed layer **202** formed thereon. In this embodiment, the underlying substrate (which is typically a base silicon layer) may be separated from the overlying silicon layer (also referred to as the active layer) by etching laterally through the insulator layer as discussed below.

FIG. **3** illustrates forming an LED structure **302** over the substrate **102** in accordance with an embodiment of the present invention. The LED structure **302** may include a first contact layer **304**, a first cladding layer **306**, an active layer **308**, a second cladding layer **310**, and a second contact layer **312**. An optional buffer layer **314** may also be used.

The buffer layer **314** comprises one or more layers of a material formed over substrate **102** (e.g., the porous layer **104** and/or the seed layer **202**) and acts as a nucleation layer during the epitaxy growth process for the formation of the subsequent layers of the LED structure **302**. Depending upon the type of substrate and the connections to the first and second contact layers **304** and **312**, respectively, a buffer layer may be desirable between the first contact layer **304** and the substrate **102** (or the porous layer **104** or the seed layer **202**). For example, with some types of substrates, such as SiC and Si substrates, a buffer layer, such as AlN or AlGaN, may be desirable to aid in the epitaxial growth of a group III-N compound on the SiC substrate.

The buffer layer **314** may be formed of, for example, a group III-N based material, a metal nitride, a metal carbide, a metal carbon-nitride, a pure metal, a metal alloy, silicon-containing material, or the like, formed by, for example, metal organic CVD (MOCVD), MOVPE, plasma-enhanced CVD (PECVD), RPCVD, MBE, HVPE, LPE, chloride VPE (Cl-VPE), or the like. Examples of materials that may be used for the buffer layer **314** include SiC, ZnO, GaN, InN, AlN, InGaN, AlGaN, AlInN, AlInGaN, and the like. The buffer layer **314** may further include a plurality of layers, such as a plurality of AlN layers and a plurality of silicon-doped GaN layers stacked in an alternating pattern. Buffer layer **314** may be doped with a p-type or an n-type impurity, or substantially un-doped.

The first contact layer **304** is formed over the buffer layer **314**. The first contact layer **304** may be formed of a group III-nitride (or other group V element). In an embodiment, the first contact layer **304** is formed of a group III-N compound with an n-type conductivity (e.g., n-GaN) and disposed by, for example, a selective epitaxial growth process such as a MBE, MOCVD, HVPE, LPE, or the like. The group III-N material may include, for example, GaN, InN, AlN, $In_xGa_{(1-x)}N$, $Al_xGa_{(1-x)}N$, $Al_xIn_yGa_{(1-x-y)}N$, or the like. Other materials, including other group V elements instead of nitride, may be used.

The optional first cladding layer **306** is formed over the first contact layer **304**. Similar to the first contact layer **304**, the first cladding layer **306** may be formed of a group III-N compound (or other group V element). In an exemplary embodiment, the first cladding layer **306** comprises a group III-N compound having n-type conductivity (e.g., n-AlGaN). The formation methods of the first cladding layer **306** may be essentially the same as the method for forming first contact layer **304**.

The light-emitting layer **308** (also sometimes referred to as an active layer) is formed on the first cladding layer **306**. The light-emitting layer **308** may include a homojunction, heterojunction, single-quantum well (SQW), multiple-quantum well (MQW), or the like, structure. In an exemplary embodiment, the light-emitting layer **308** comprises undoped n-type gallium indium nitride ($Ga_xIn_yN_{(1-x-y)}$). In alternative embodiments, light-emitting layer **308** includes other commonly used materials such as $Al_xIn_yGa_{(1-x-y)}N$. In yet other embodiments, light-emitting layer **308** may be a multiple quantum well including multiple well layers (such as InGaN) and barrier layers (such as GaN) allocated in an alternating pattern. Again, the formation methods include MOCVD, MBE, HVPE, LPE, or other applicable CVD methods. The total thickness of the light-emitting layer **308** is preferably between about 5 nm and about 200 nm.

An optional second cladding layer **310** may be formed on light-emitting layer **308**. In an embodiment, the second cladding layer **310** comprises a material similar to that of first cladding layer **306**, such as AlGaN, except the second cladding layer **310** may be doped to p-type. The formation method of the second cladding layer **310** may be essentially the same as the method for forming the first cladding layer **306**, except having an opposite type of conductivity.

The second contact layer **312** is formed on the second cladding layer **310**. The second contact layer **312** may be formed of essentially the same or different materials, and using similar methods, as the formation of first contact layer **304**, except the conductivity type of the second contact layer **312** is opposite to that of the first contact layer **304**.

Also shown in FIG. **3** is an optional reflective layer **316** formed over the top of the group III-V LED stack. The reflective layer **316** acts to reflect light emitted from the light-emitting layer **308** toward and through the second contact layer **312** back toward the first contact layer **304**, which will act as the light-emitting face of the LED device as discussed below. The optional reflective layer **316** may comprise a single layer, such as a layer of reflective metal (e.g., Al, Ag, or the like), or a multiple layer structure, such as a distributed Bragg reflector, an omni-directional reflector, or the like. In other embodiments in which the second contact layer **312** is highly reflective, the reflective layer **316** may not be necessary.

FIG. **4** illustrates forming a conductive substrate **402** on the LED structure **302** in accordance with an embodiment of the present invention. The conductive substrate **402** is formed over the LED structure **302** and provides an electrical contact to the second contact layer **312** (and/or the reflective layer **316**). The conductive substrate **402** may be formed of any suitable conductive material, such as doped silicon, metal, metal alloy, or the like. The conductive substrate **402** preferably has a thickness greater than about 50 μm.

In an embodiment, the conductive substrate **402** is formed by electroplating. In this embodiment, the wafer is coated with a seed layer (not shown) and then placed in an electroplating solution containing ions of a metal, such as nickel, chromium, copper, or the like, and a voltage is applied. For example, if nickel is to be utilized for the conductive substrate **402**, the wafer is placed in a solution comprising $NiSO_4$, $NiCl_2$, and H_2O_2. The wafer surface is electrically connected to the negative side of an external DC power supply such that the wafer functions as the cathode in the electroplating process. A nickel anode is also immersed in the solution and is attached to the positive side of the power supply. The nickel atoms of the anode are oxidized to form Ni^{2+} ions. The Ni^{2+} ions are released from the anode and dissolve into the solution. As the positive nickel ions arrive at the negative-biased cathode, e.g., the wafer, they are reduced to nickel metal that plates the wafer surface.

In another embodiment, the conductive substrate **402** is formed of silicon. In this embodiment, a silicon substrate is bonded to the surface of the second contact layer **312**, thereby forming the conductive substrate **402** as illustrated in FIG. **4**. The silicon substrate that is bonded is preferably a bulk silicon substrate doped with ions having a conductivity type the same as the second contact layer **312** of the LED structure **302**. For example, in an embodiment in which the second contact layer **312** is a p-type conductivity material, the silicon substrate is doped with boron ions or other p-type ions. The silicon substrate may be bonded to the second contact layer **312** through Au—Si eutectic bonding (depositing Au on **312** first) or metal-to-metal bonding (depositing Au or Cu on both substrates).

FIG. **5** illustrates removing the substrate **102** and the porous layer **104** in accordance with an embodiment of the present invention. The substrate **102** may be separated from the LED structure **302** by utilizing a mechanical detach process, such as a water jet process. A water jet process utilizes a stream of water to mechanically etch laterally from the edges of the substrate. Because of the porosity of the porous layer **104**, the porous layer **104** may be cleaved, thereby separating the substrate **102** from the LED structure **302**. The substrate **102** may advantageously be reused, thereby reducing waste and reducing costs.

In another embodiment, the porous layer **104** may be removed by a chemical etch process. In this embodiment, an aqueous solution of 49% hydrofluoric acid: 30% H_2O_2 (1:5) may be used to laterally etch the porous layer **104** from the edges of the substrate **102**. The hydrofluoric acid has an etch selectivity rate of the porous layer **104** to the substrate **102** (and other layers of the LED structure **302**) of about 1-to-100,000. Because of the high etch selectivity rate, a lateral etch is possible without causing substantial damage to the substrate **102** or the LED structure **302**. Other splitting methods include: thermal stress, perforation, and inserting a solid wedge.

FIG. **6** illustrates removing the seed layer **202** in accordance with an embodiment of the present invention. The seed layer **202** may be removed by, for example, a wet dip in a solution of hydrofluoric acid, nitric acid, and acetic acid (commonly referred to as an HNA solution) or a solution of potassium hydroxide. These solutions will remove any residue of the porous layer **104** as well as remove the seed layer **202**. In some embodiments the buffer layer **314** may be removed by wet etching to further improve the electrical contact to the first contact layer **304**. As a result, a good electrical contact may be made to the lower portion of the LED structure **302**.

Thereafter, processes may be performed to complete the LED device. For example, electrical contacts (front-side and/or back-side contacts) may be formed to the first and second contact layers **304** and **312**, respectively, passivation layers may be formed, and the LED device may be diced and packaged.

Similar process could be applied to a somewhat more expensive SOI substrate. Embodiments involving SOI substrates do not require the formation of porous layers because the buried oxide layer in an SOI substrate can be selectively etched. For an embodiment involving an SOI wafer, the substrate in FIG. **2** comprises a silicon substrate **102**, a buried oxide layer **104**, and a topmost silicon layer **202**. Buried oxide layer **104** can be selectively removed by a hydrofluoric-acid solution. For example, immersing the SOI substrate in a hydrofluoric acid solution having about 1-10% by volume of HF will preferentially etch the oxide layer while only slowly etching the topmost silicon layer **202** and the silicon substrate **102**. After the buried oxide layer **104** is removed, the subsequent process steps shown in FIGS. **3** through **6** can be carried out as previously described. So, for example, the topmost silicon layer **202** can be removed in the same manner as the previously described seed layer removal process shown in FIG. **6**.

FIGS. **7-11** illustrate another method of forming an LED device in accordance with an embodiment of the present invention. Referring first to FIG. **7**, there is shown a substrate **702** having a doped layer **704**. The substrate **702** may be of a similar material as the substrate **102** discussed above. The doped layer **704** is preferably formed by implanting p-type ions into the substrate **702**. For example, the doped layer **704** may be formed by implanting boron ions at a dose of about 1×10^{13} atoms/cm^2 to about 1×10^{16} atoms/cm^2 and at an energy of about 1 KeV to about 50 KeV. A post-implantation thermal anneal may be performed if needed. The doped layer **704** preferably has a thickness of about 0.1 μm to about 10 μm.

The doped layer **704** provides additional structural strength during the fabrication of the LED device as compared to the embodiment discussed above with reference to FIGS. **1-6**. A pre-fabricated porous layer **104** (see FIG. **1**) is more fragile and in some embodiments may fail to provide sufficient structural support during the fabrication of the LED device. In these embodiments, it is preferred that the doped layer **704** be formed, which will be converted to a porous layer in subsequent processing steps. The use of the doped layer **704** also provides an increased thermal budget tolerance.

FIG. **8** illustrates a method of forming LED structure **802** in accordance with an embodiment of the present invention. As illustrated in FIG. **8**, the LED structure **802** is formed between sacrificial plugs **804**. As will be discussed in greater detail below, the sacrificial plugs **804** will be removed in a subsequent step to form a porous layer **1002**. Alternatively, some openings **904** are etched through the LED structure to form porous layer **1002**.

The sacrificial plugs **804** are preferably formed of a material having a high etch selectivity with respect to the substrate **702**. For example, in an embodiment in which the substrate **702** is a silicon substrate, the sacrificial plugs **804** may comprise a silicon dioxide material. In this embodiment, the sacrificial plugs **804** may be formed by depositing and patterning a blanket layer of silicon dioxide. A blanket layer of silicon dioxide may be formed by, for example, thermal oxidation or by chemical vapor deposition (CVD) techniques using tetra-ethyl-ortho-silicate (TEOS) and oxygen as a precursor. Alternatively, the sacrificial plugs **804** may be formed of other dielectric materials. For example, silicon nitride, silicon oxynitride, the like, formed through a process such as CVD may also be used. The sacrificial plugs **804** preferably have a thickness of about 1 μm to about 6 μm.

The blanket layer of silicon dioxide may then be patterned using photolithography techniques known in the art. Generally, photolithography techniques involve depositing a photoresist material and irradiating the photoresist material in accordance with a pattern. Thereafter, the photoresist material is developed to remove a portion of the photoresist material. The remaining photoresist material protects the underlying material during subsequent processing steps, such as etching. In this case, the photoresist material is utilized to pattern the sacrificial plugs **804** as illustrated in FIG. **8**.

Thereafter, the LED structure **802** may be formed. The LED structure **802** and the buffer layer **314** may have similar layers formed of similar materials as discussed above with reference to the LED structure **302** and the buffer layer **314**, wherein like reference numerals refer to like elements.

Referring now to FIG. **9**, the sacrificial plugs **804** are removed in accordance with an embodiment of the present invention. In an embodiment in which the sacrificial plugs **804** comprise silicon dioxide, the sacrificial plugs **804** may be removed by a wet dip in hydrofluoric acid having a concentration of about 1-10% by volume. The HF etch preferentially etches the sacrificial plugs **804** in that HF only slowly etches the doped layer **704** unless the etch process is enhanced electrochemically.

Also illustrated in FIG. **9** is the formation of spacers **902** along the sidewalls of openings **904**. The spacers **902**, which should help prevent the upper and lower layers of the LED structure **802** from being shorted, preferably comprise a dielectric material having a high-etch selectivity compared to the LED structure **802** and the doped layer **704**. For example, in the embodiment in which the doped layer **704** comprises silicon, the spacers may be formed of a material such as silicon dioxide, silicon nitride (Si_3N_4), or another nitrogen-containing layer, such as Si_xN_y, silicon oxynitride SiO_xN_y, silicon oxime $SiO_xN_y:H_z$, or a combination thereof. In a preferred embodiment, the spacers **902** are formed of a blanket layer of silicon nitride formed by, for example, CVD techniques using silane and ammonia as precursor gases as a precursor to a thickness of about 5 nm to about 100 nm. The spacers **902** may be patterned by performing an anisotropic dry etch process.

FIG. **10** illustrates the conversion of the doped layer **704** (see FIG. **9**) into a porous layer **1002** in accordance with an embodiment of the present invention. The removal of the sacrificial plugs **804** allows the conversion of the doped layer **704** into the porous layer **1002** by a chemical etch process from the opening **904** as well as laterally along the edges of the substrate **702**. The doped layer **704** may be converted into the porous layer **1002** by, for example, an electro-chemical anodization process using an electrolyte composition of aqueous solution of hydrofluoric acid (about 20% by mass) and ethylic alcohol with an anodic current density of about 1 mA/cm^2 to about 200 mA/cm^2. It should be noted that the concentration of the hydrofluoric acid is greater in this step as compared to the etching process used above with reference to FIG. **9** to remove the sacrificial plugs **804**, and in this step the etch is also electrochemically enhanced. Using a lower concentration of hydrofluoric acid to remove the sacrificial plugs **804** prevents the hydrofluoric acid from etching or over processing the doped layer **704**. It should be noted, however, that over processing the doped layer **704** at this point may cause the substrate **702** to detach prior to forming the conductive substrate as discussed below and, therefore, the concentration of the hydrofluoric acid should be adjusted such that the doped layer **704** is converted to a porous layer without completing removing the doped layer **704**, thereby detaching the substrate **702** from the LED structure **802**.

FIG. **11** illustrates forming a conductive substrate **1102** in accordance with an embodiment of the present invention. The conductive substrate **1102** may be formed in a similar manner as the conductive substrate **402** discussed above with reference to FIG. **4**, and will not be described again.

FIG. **12** illustrates removing the substrate **702** and the porous layer **1002** in accordance with an embodiment of the present invention. The substrate **702** and the porous layer **1002** may be removed in a similar manner as the substrate **102** and the porous layer **104** are removed as discussed above with reference to FIG. **5**.

It should be noted that the LED structures may be patterned in any suitable pattern with respect to a plan view. For example, the LED structure **802** may be formed in a matrix of squares, rectangles, circles, ellipses, and the like. Furthermore, a plan view may have staggered shapes or be arranged in any number of patterns.

It should be further noted that the LED structures **302** and/or **802** are illustrated as planar devices for illustrative purposes only. In some embodiments, it may be desirable to form the LED structures **302** and/or **802** on a textured substrate. A textured substrate may be formed, for example, by etching recesses and/or forming raised regions via an epitaxial growth. By using a textured surface, the surface area of light-emitting layers may be increased, thereby increasing the light efficiency of the LED device for a given size of a substrate.

While the above description assumes that the LED structure has a p-type surface facing the conductive substrate, one of ordinary skill in the art will appreciate that embodiments of the present invention may utilize an LED structure such that an n-type surface faces the conductive substrate. In these embodiments, the first contact layer **304** and the first cladding layer **306** would have p-type conductivity, and the second cladding layer **310** and the second contact layer **312** would have n-type conductivity.

Although the present invention and its advantages have been described in detail, it should be understood that various changes, substitutions, and alterations can be made herein without departing from the spirit and scope of the invention as defined by the appended claims. Moreover, the scope of the present application is not intended to be limited to the particular embodiments of the process, machine, manufacture, and composition of matter, means, methods, and steps described in the specification. As one of ordinary skill in the art will readily appreciate from the disclosure of the present invention, processes, machines, manufacture, compositions of matter, means, methods, or steps, presently existing or later to be developed, that perform substantially the same function or achieve substantially the same result as the corresponding embodiments described herein may be utilized according to the present invention. Accordingly, the appended claims are intended to include within their scope such processes, machines, manufacture, compositions of matter, means, methods, or steps.

What is claimed is:

1. A method of forming a light-emitting diode (LED) device, the method comprising:

providing a silicon-on-insulator (SOI) substrate comprising a silicon substrate, a buried oxide layer, and a topmost silicon layer, wherein the topmost silicon layer contains a porous layer;

forming an LED structure over the topmost silicon layer of the SOI substrate;

forming a conductive substrate over the LED structure in a manner such that the LED structure is disposed between the porous layer and the conductive substrate; and

etching the porous layer to separate the silicon substrate from the LED structure.

2. The method of claim 1, further comprising removing the topmost silicon layer from the LED structure.

3. The method of claim 1, wherein the step of etching the porous layer comprises exposing the porous layer to a hydrofluoric-acid solution.

4. The method of claim 1, wherein the forming the conductive substrate over the LED structure is performed at least in part by electroplating.

5. The method of claim 4, wherein the electroplating comprises electroplating nickel.

6. The method of claim 1, wherein the forming the conductive substrate comprises forming a doped silicon layer over the LED structure.

7. The method of claim 1, wherein the forming the conductive substrate comprises bonding a second silicon substrate to the LED structure.

8. The method of claim 7, wherein the second silicon substrate comprises a silicon substrate doped with p-type ions.

9. A method of fabricating a light-emitting diode (LED) device, comprising:

providing a first substrate;

forming a porous layer on the first substrate;

forming an LED structure over the porous layer, wherein the LED structure includes a light-emitting layer disposed between a first group III-V compound layer and a second group III-V compound layer, the first and second group III-V compound layers having different types of conductivity;

attaching a second substrate to the LED structure, such that the LED structure is disposed between the first substrate and the second substrate; and

cleaving the porous layer, thereby separating the first substrate from the LED structure and the second substrate.

10. The method of claim 9, wherein the forming the porous layer comprises converting a portion of the substrate into the porous layer through an electro-chemical anodization process.

11. The method of claim 9, wherein the cleaving the porous layer comprises performing a water jet mechanical detach process to the porous layer.

12. The method of claim 9, wherein the cleaving the porous layer comprises performing a chemical etch process to the porous layer.

13. The method of claim 9, wherein the first substrate comprises a bulk silicon substrate.

14. The method of claim 9, wherein the first substrate comprises a silicon-on-insulator (SOI) substrate, a sapphire substrate, or a silicon carbide substrate.

15. The method of claim 9, wherein the second substrate comprises a conductive substrate.

16. The method of claim 9, further comprising:

forming a seed layer between the porous layer and the LED structure; and

removing the seed layer after the cleaving the porous layer.

17. The method of claim 9, further comprising: forming a reflective layer between the LED structure and the second substrate.

18. A method of fabricating a light-emitting diode (LED) device, comprising:

providing a bulk silicon substrate;

converting a surface portion of the bulk silicon substrate into a porous layer;

forming a seed layer over the porous layer;

forming an LED structure over the seed layer, wherein the LED structure includes a light-emitting layer disposed between a first group III-V compound layer and a second group III-V compound layer, the first and second group III-V compound layers having different types of conductivity;

bonding a conductive substrate to the LED structure, such that the bulk silicon substrate and the conductive substrate are disposed on opposite sides of the LED structure; and

separating the bulk silicon substrate from the LED structure and the conductive substrate at least in part by cleaving the porous layer through a mechanical detach process or through an etching process.

19. The method of claim 18, wherein the converting comprises performing an electro-chemical anodization process to the surface portion of the bulk silicon substrate.

20. The method of claim 18, wherein:

the mechanical detach process comprises applying a stream of water laterally to the porous layer; and

the etch process comprises applying a hydrofluoric acid to the porous layer.

21. The method of claim 18, further comprising: forming a reflective layer between the LED structure and the conductive substrate.

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